Spacetime Realism and Quantum Gravity*

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Abstract

Sophisticated substantivalism is defended as a response to the hole argument. It is also shown to be an interpretation of spacetime that is compatible with a range of approaches to canonical quantum gravity.

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Outline of Talk

- According to Earman and Norton (1987), Einstein's *hole argument* shows that spacetime *substantivalists* are committed to a radical form of indeterminism. The only way to save the possibility of determinism is to endorse a *relationist* interpretation of the geometry of spacetime.
- Many philosophers have since disagreed (Brighouse 1994, Butterfield 1989, Hoefer 1996, Maidens 1993, Maudlin 1990). A frequent response is that one can regard all isomorphic models of general relativity as representing the same physical possibility (*Leibniz Equvalence*) **AND** regard spacetime as a basic, substantival and concrete entity.
- Recently Belot and Earman (2000) have claimed that this *"sophisticated form of substantivalism"* lacks a "coherent and plausible motivation" (2000, 167). They suggest that philosophers should take account of the link between different interpretative stances towards the spacetime of classical general relativity and distinct approaches to overcoming the technical and conceptual problems of canonical quantum gravity. They claim that only *straightforward substantivalism* and relationalism underwrite interesting programmes.
- I suggest that the opposite is the case – that a variety of distinct approaches to quantum gravity involve a form of sophisticated substantivalism. By way of illustration I discuss those of Julian Barbour and Carlo Rovelli, both discussed by Belot and Earman.

Substantivalism and Relationism

Substantivalists understand the existence of spacetime in terms of the existence of its pointlike parts, and gloss spatiotemporal relations between material events in terms of the spatiotemporal relations between points at which they occur. Relationists will deny that spacetime points enjoy this robust sort of existence, and will accept spatiotemporal relations between events as primitive.
(Belot and Earman, *forthcoming*)

a modern-day substantivalist thinks that spacetime is a kind of thing which can, in consistency with the laws of nature, exist independently of material things (ordinary matter, light, and so on) and which is properly described as having its own properties, over and above the properties of any material things that may occupy parts of it. (Hoefer 1996)

The Hole Argument

$d : M \to M$, $d|_{t \le 0} = I$
$\mathcal{M} =< M, g, T >$
$\mathcal{M}' =< M, d * g, d * T >$

1. General covariance $\Rightarrow$ If $\mathcal{M}$ is a model of GR then so is $\mathcal{M}'$
2. Substantivalism $\Rightarrow$ $\mathcal{M}$ and $\mathcal{M}'$ represent **distinct** physically possible worlds
3. $\mathcal{M}$ and $\mathcal{M}'$ are identical for $t \le 0 \Rightarrow$ **indeterminism**

NOTE: Relationism $\Rightarrow$ **Leibniz Equivalence** – that $\mathcal{M}$ and $\mathcal{M}'$ represent the *same* possible world.

3 responses to the hole argument

1. **Straightforward substantivalism**
   Bite the bullet. Concede that the hole argument shows that substantivalists are committed to viewing GR as an indeterministic theory.
   - The indeterminism involved does not effect predictions.

2. **Relationism**
   Avoid indeterminism by claiming that there are no substantival entities corresponding to the points of the manifold M.
   - Formulate physics without a background manifold?
   - What's the status of the metric field?
   - How to understand vacuum spacetimes

3. **Sophisticated substantivalism**
   Isomorphic models $\mathcal{M}$ and $\mathcal{M}'$ represent the same physical possibility ($=$ LE) **AND** spacetime points exist as fundamental entities.
   - LE accords with the practice of physics
   - the metric (plus manifold) gets its natural interpretation as spacetime
   - $\mathcal{M}$ and $\mathcal{M}'$ can only be regarded as representing distinct possible worlds if spacetime points have **primitive identity**. Denying that they do is good metaphysics independently of the hole argument.

Sophisticated substantivalism and Quantum Gravity

- Different interpretations of classical GR map onto different approaches to overcoming the technical and conceptual problems of canonical quantum gravity.

- Should one of these approaches prove ultimately successful, then there would be reason to prefer the corresponding interpretation of the classical theory.

- Belot and Earman (2000) discuss a number of approaches to canonical quantum gravity including those of Karel Kuchař, Carlo Rovelli and Julian Barbour.

  They claim that both straightforward substantivalism and relationism underwrite distinctive and intruiging approaches to QG. In contrast sophisticated substantivalism is

  > a pallid imitation of relationism, fit only for those substantivalists who are unwilling to let their beliefs about the existence of space and time face the challenges posed by contemporary physics. (**Pre-Socratic Quantum Gravity**, *forthcoming*)

Rovelli's relationism

Einstein's identification between gravitational field and geometry can be read in two alternative ways:

i. as the discovery that the gravitational field is nothing but a local distortion of spacetime geometry; or

ii. as the discovery that *spacetime geometry is nothing but a manifestation of a particular field*, the gravitational field.

The choice between these two points of view is a matter of taste, at least as long as we remain within the realm of nonquantistic and nonthermal general relativity. I believe, however, that the first view, which is perhaps more traditional, tends to obscure, rather than enlighten, the profound shift in the view of spacetime produced by general relativity. . .

[In light of view ii] it is perhaps more appropriate to reserve the expression *spacetime* for the differential manifold and to use the expression *matter* for everything dynamical. . . *including the gravitational field*. . .

physical reality is now described as a complex interacting ensemble of entities (fields), the location of which is only meaningful with respect to one another.
(Rovelli, *Halfway through the woods*, 193–194)

GR as a constrained Hamiltonian system

Restricted to S, g defines a Riemannian 3-metric q_{ab} on S.

It also defines the extrinsic curvature K_{ab} of S, a tensor defined on S which is related to the rate of change of q_{ab} as Σ is 'wafted through' M.

Any pair (q_{ab}, K_{ab}) defined on Σ corresponds to a spacelike hypersurface of some model of GR **iff**

$$\begin{array}{lcl} R + (K^a_{\ a})^2 - K^{ab}K_{ab} = 0 & \Leftrightarrow & G_{00} = 0 \\ \nabla^a K_{ab} - \nabla_b K^a_{\ a} = 0 & \Leftrightarrow & G_{0b} = 0 \end{array}$$

Quantization

In general there are two options when quantizing a gauge theory:

1. Construct the reduced phase space to obtain a genuine Hamiltonian theory and quantize in the standard way

2. Impose the constraints after quantization

Rovelli *et al.* take the second option.

The quantum states $\Psi[q_{ab}]$ are elements of the space of complex functions over Riem(Σ)

Physical states are those which are annihilated by quantum operator versions of the constraints:

$$\hat{H}_a[\hat{q}_{ab}, \hat{K}_{ab}]\Psi[q_{ab}] = 0$$

$$\hat{H}[\hat{q}_{ab}, \hat{K}_{ab}]\Psi[q_{ab}] = 0$$

Rovelli on Loop Quantum Gravity

Loop quantum gravity is a rather straightforward application of quantum mechanics to hamiltonian general relativity. . . the quantum states turn out to be represented by (suitable linear combinations of) spin networks. A spin network is an abstract graph with links labeled by half-integers.

Intuitively, we can view each node of the graph as an elementary "quantum chunk of space". The links represent (transverse) surfaces separating the quanta of space. The half-integers associated with the links determine the (quantized) areas of these surfaces. The spin networks represent relational quantum states: they are not located in space. Localization must be defined in relation to them. For instance, if we have, say, a matter quantum exitation, this will be located on the spin network; while the spin network itself is not located anywhere.
(**Quantum spacetime: what do we know?**, qr-qc/9903045)

GR as a geodesic principle

Superspace is chosen as the fundamental configuration space. This is the space obtained from the space of Riemannian metrics defined on Σ by *identifying isometric spaces* – Riem(Σ)/Diff(Σ).

The action principle of general relativity can be cast as a (degenerate) geodesic principle on this space.

- A literal interpretation of this formulation involves regarding **space**, not spacetime, as the fundamental entity.
- The choice of superspace rather than Riem(Σ) supports a "sophisticated" rather than a "straightforward" substantivalist interpretation of space.
- The theory is nonetheless indeterministic. (Formulating GR as a geodesic principle on **conformal** superspace promises to yield a deterministic theory – gr-qc/9911071.)

Barbour’s ‘timeless’ interpretation of quantum gravity

Viewed as a geodesic principle on configuration space, GR is “timeless”: the initial data consist of a point and a **direction** only.

Barbour’s is a many worlds or “many instants” interpretation of quantum gravity. The possible instants are (intrinsically specified) **spaces** (perhaps containing matter).

Conclusions

- Substantivalism appears to be compatible with many approaches to quantum gravity.

- The opposition between "sophisticated" and "straightforward" varieties of substantivalism **may** map onto distinct approaches (Kuchař versus Rovelli).

- No approach to canonical quantum gravity appears to support relationism in the sense that space or spacetime and its geometrical structure is reduced to structural properties of matter, or that it cannot exist without matter.

- A more interesting interpretative question concerns whether space might after all be more fundamental than spacetime.